

Fluorine Abundances in the Milky Way Bulge

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ABSTRACT

Fluorine (^{19}F) abundances are derived in a sample of 6 bulge red giants in Baade’s Window. These giants span a factor of 10 in metallicity and this is the first study to define the behavior of ^{19}F with metallicity in the bulge. The bulge results show an increase in F/O with increasing oxygen. This trend overlaps what is found in the disk at comparable metallicities, with the most oxygen-rich bulge target extending the disk trend. The increase in F/O in the disk arises from ^{19}F synthesis in both asymptotic giant branch (AGB) stars and metal-rich Wolf-Rayet (WR) stars through stellar winds. The lack of an s-process enhancement in the most fluorine-rich bulge giant in this study, suggests that WR stars represented a larger contribution than AGB stars to ^{19}F production in the bulge when compared to the disk. If this result for fluorine is combined with the previously published overall decline in the O/Mg abundance ratios in metal-rich bulge stars, it suggests that WR winds played a role in shaping chemical evolution in the bulge. One star in this study exhibits a very low value of F/O while having a large O-abundance; this chemical mixture can be understood if this star formed from gas that was enriched by metal-poor core-collapse supernovae and may indicate that chemical evolution in the bulge was inhomogeneous.

Subject headings: stars: abundances; Galaxy: abundances; Galaxy: bulge

1. INTRODUCTION

Understanding how chemical evolution has proceeded in the Galactic bulge can provide clues for models of bulge formation and evolution. It is not known, for example, whether the

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Milky Way bulge was formed rapidly in a single collapse or via secular dynamical evolution driven by the disk. Certain elemental abundance ratios can be used to infer timescales for chemical enrichment within a particular stellar population. The most studied of these ratios involves comparing the abundances of the so-called α -elements (such as O, Mg, or Ca), which are produced via massive-star core-collapse supernovae of type II (SNII), to abundances of iron, which is produced in SN Ia. Probing elemental species that are created in other astrophysical sites, such as AGB stars or WR stars, can add further constraints to bulge formation scenarios.

The first study to provide chemical abundance distributions of several elements in a sample of bulge red giants was McWilliam & Rich (1994). It is only within the last few years that additional abundance studies have appeared, all of which rely on the 8-10m class telescopes. These recent studies include, in the optical, Zoccali et al. (2006); Fulbright et al. (2006, 2007); Lecureur et al. (2007); McWilliam et al. (2007) and, in the infrared, Rich & Origlia (2005); Cunha & Smith (2006); Rich et al. (2007) and Melendez et al. (2008). Although a relatively large number of bulge targets have been studied so far, the abundance patterns of the Galactic bulge population continue to be probed in increasing detail.

One element that can add new insight into the nature of chemical evolution in the bulge is fluorine. Understanding the origins of this light element has advanced considerably in recent years, based upon ^{19}F abundances derived from infrared vibration-rotation lines of HF (Jorissen et al. 1992; Cunha et al. 2003; Cunha & Smith 2005; Smith et al. 2005). Renda et al. (2004) use the observed abundances to model the Galactic chemical evolution of fluorine, with its synthesis occurring primarily in three different astrophysical sites: in AGB stars as a result of He-burning (Goriely et al. 1989; Forestini et al. 1992; Jorissen et al. 1992), in SN II via neutrino nucleosynthesis (Woosley et al. 1990; Woosley & Weaver 1995), and in WR stars as a result of He-burning and extensive stellar winds (Meynet & Arnould 2000). Renda et al. (2004) found that neutrino nucleosynthesis was the important source of ^{19}F in the early Galaxy (at low metallicity); however, the fluorine abundances found in near-solar metallicity stars required significant contributions from both AGB stars and WR winds.

This paper concentrates on determining fluorine abundances in a sample of red giants of the Galactic bulge and these results are combined with previously derived abundances from other elements. Observational evidence for fluorine production in WR stars, compared to AGB stars or neutrino nucleosynthesis in SN II, is discussed as well as the implication for the nature of chemical evolution in the bulge.

2. OBSERVATIONS

The target stars for this analysis of fluorine were taken from our previous infrared high-resolution spectroscopic study of Galactic bulge giants (Cunha & Smith 2006). The sample, which is composed of 5 K- and 2 M-giants, is presented in Table 1. Details about the nature of these stars, all of which lie in Baade’s Window, can be found in Cunha & Smith (2006). The spectra were observed in queue mode with the 8.1m Gemini South telescope and the NOAO spectrograph Phoenix (Hinkle et al. 1998) at a resolution $R \sim 50,000$; these were centered at 23400\AA in order to include the HF 1-0 R9 line and covered a window of $\sim 120\text{\AA}$. The K-giants in our sample were observed in May and July 2004; June and July 2005 (same spectra were analyzed previously for Na in Cunha & Smith 2006); while the two M-giant observations were taken more recently during one night in June 2007. A description of the Phoenix observations and the reduction of the high-resolution spectra can be found in Cunha & Smith (2006) and Smith et al. (2002).

3. Analysis

All target stars were previously analyzed in the literature and had stellar parameters and microturbulent velocities (Table 1) derived in Cunha & Smith (2006). The effective temperatures were obtained using calibrations of infrared photometry (J-K and/or V-K colors) and extinction maps of Stanek (1996). The surface gravities were derived from standard relations between stellar luminosity and mass as defined by isochrones corresponding to 10 Gyr by Girardi et al. (2000). The microturbulent velocities were estimated from measurements of CO molecular lines which are also present in the observed Phoenix spectra in the K-band. More detailed information on the derivation of the stellar parameters can be found in Cunha & Smith (2006).

The fluorine abundances are derived from the HF 1-0 R9 line at 23357\AA . The reliability of this line as an accurate abundance indicator has been verified in Cunha et al. (2003) from comparisons with other HF lines (which were analyzed in Jorissen et al. 1992). Fluorine abundances were obtained from synthetic spectra computed with an updated version of the synthesis code MOOG (Snedden 1973) and adopting MARCS model atmospheres (Gustafsson et al. 1975). Figure 1 shows both synthetic and observed spectra for one sample star. The derived fluorine abundances are presented in Table 1 in the nomenclature of $A(x) = \text{Log}[N(x)/N(H)] + 12.0$.

In addition to the ^{19}F abundances in Table 1, values for $A(\text{Na})$ are also shown, with 5 of the Na abundances taken from Cunha & Smith (2006). They are presented here along with

the two new Na abundance results for BMB78 and BMB289; from the Na I line at 23379Å. Oxygen abundances are also included for completeness with abundances taken from Cunha & Smith (2006).

4. DISCUSSION

The chemical evolution of the Galactic bulge has been modelled recently by Ballero et al. (2007), who focused on the constraints provided by recently published abundances of iron and α -elements in bulge red-giants. Although at the moment such models do not predict the evolution of the element fluorine in particular, the behavior of the fluorine abundances derived in this study can be used to interpret some aspects of chemical evolution in the bulge population.

This interpretation begins with Figure 2, where the ratio of F/O ($\text{Log}[N(\text{F})/N(\text{O})]$) is plotted as a function of the oxygen abundance, $A(\text{O})$, and oxygen is used as a proxy for the overall metallicity. The five bulge ^{19}F measurements are shown as the red circles, with estimated errors indicated. All results to-date for Galactic field stars are also plotted, with these abundances taken from Cunha et al. (2003), Cunha & Smith (2005), and Cunha et al. (2008). The two populations shown in Figure 2 (the Galactic field and the bulge) both exhibit generally increasing values of F/O as the O-abundance increases. Overall, the bulge giants overlap the trend set by the field stars, with the most O-rich bulge star studied (IV-072) apparently defining a smooth extension of the field-star trend to ever increasing oxygen abundances. One bulge M-giant, BMB78, defies the general trend by having a relatively low value of F/O given its high oxygen abundance.

The solid line in Figure 2 represents the predicted values of $^{19}\text{F}/^{16}\text{O}$, as a function of metallicity, derived from the Woosley & Weaver (1995) SN II yields, convolved with a Salpeter mass function and an upper limit of $40M_{\odot}$; the ^{19}F from these models is produced by neutrino nucleosynthesis. More recently, however, Heger et al. (2005) argue that ^{19}F production via neutrino nucleosynthesis should be lowered by about a factor of two, due to reduced cross-sections, and the dashed line in Figure 2 is a shift of the Woosley & Weaver (1995) yields downward by 0.3 dex as a simple way of viewing these suggested revisions. It is clear from the results in the figure that at the lowest metallicities, the observed values of F/O for field disk stars tend to approach the values predicted by the yields in which ^{19}F is synthesized via neutrino nucleosynthesis. The Sun and near-solar metallicity field stars, however, fall above the predicted F/O values from neutrino nucleosynthesis and this difference points to significant contributions to ^{19}F production from WR and AGB stars, as suggested by Renda et al. (2004).

With four out of the five bulge stars containing larger ratios of fluorine to oxygen than can be accommodated by neutrino nucleosynthesis alone, one is left with two possibilities for ^{19}F production at high metallicities, based upon the Renda et al. (2004) model: the AGB and WR stars. Can one now attempt to distinguish between these two sites for ^{19}F production in the bulge, keeping in mind that there are no bulge-specific chemical evolution models for ^{19}F ? Looking first at the AGB stars, Jorissen et al. (1992) pointed out that there is a positive correlation between F/O with the s-process abundances (their figure 12) and this correlation was modelled by Goriely & Molawi (2000) for neutron capture nucleosynthesis in AGB stars. Both the model predictions and the observed correlation between fluorine and s-process abundances would suggest that the most fluorine-rich star observed in the bulge, IV-072, should be heavily enriched in s-process elements at the level of $[\text{s}/\text{Fe}] \sim +1.5$ dex, if the ^{19}F resulted from AGB production. However, McWilliam & Rich (1994) derived abundances for two s-process elements in IV-072 and obtained $[\text{Y}/\text{Fe}] = -0.02$ dex and $[\text{La}/\text{Fe}] = -0.04$ dex; far below what would be expected from AGB models and observed correlations. In addition, recent results for heavy-element abundances in three metal-rich bulge dwarfs, whose brightnesses were increased during microlensing events, do not find s-process enrichments: $[\text{s}/\text{Fe}] \sim +0.12$ dex (Zr, Ba and La from Cohen et al. 2008); -0.24 dex (Ba from Johnson et al. 2008) and -0.28 dex (Ba from Johnson et al. 2007).

Given the apparent lack of s-process enriched high-metallicity bulge stars, the best explanation for the large F/O value in IV-072 may be WR fluorine production. Such a conclusion is reached by Renda et al. (2004) for the metal-rich end of disk chemical evolution. We note, however, the cautionary points raised by Palacios et al. (2005) in regard to ^{19}F production in WR stars; rotationally-induced mixing and mass-loss prescriptions can in fact lead to either an order-of-magnitude decrease in ^{19}F production (for high-mass ($>30\text{--}80 M_{\odot}$) fast rotators at solar-to-supersolar metallicities) or an order-of-magnitude increase in ^{19}F production (for lower mass ($<30 M_{\odot}$) fast rotators at supersolar metallicities). The issue of the $^{19}\text{F}(\alpha, p)^{22}\text{Ne}$ reaction rate uncertainty raised by the downwards revision proposed by Lugaro et al (2004), appears ameliorated by the recent work of Ugalde et al (2008), which is consistent with the canonical rate of Caughlan & Fowler (1988). The large ^{19}F abundance in IV-072 may require a relatively large amount of WR-wind material sculpting the chemical evolution of the metal-rich bulge population. This conclusion, based on fluorine, agrees with conclusions that are based on the ratios of O to Mg in metal-rich bulge and disk stars by McWilliam et al. (2007).

While 4 out of 5 bulge fluorine abundances follow an increase in F/O as the stellar metallicity increases, the peculiar position of BMB78 in Figure 2 questions whether bulge metallicity increased in a monotonic fashion. This star is quite oxygen-rich yet has a low fluorine abundance: its value of $^{19}\text{F}/^{16}\text{O}$ is consistent with the yields predicted from neutrino

nucleosynthesis only. The low value of F/O in BMB78 does not result from errors within the analysis. Errors in the HF and OH abundances are discussed in detail in Cunha et al. (2003) and Smith et al, (2003), respectively. Abundance uncertainties are expected to be ± 0.15 dex for fluorine and ± 0.20 dex for oxygen. Since both HF and OH exhibit similar sensitivities to changes in stellar parameters, their ratio is effectively less sensitive to analysis uncertainties. As BMB78 falls about 1.0 dex below the trend defined by the other stars, analysis errors are unlikely to explain its low value of F/O. Since the ^{19}F -yield from SN II neutrinos is sensitive to the metallicity of the supernova progenitor star, it is possible that BMB78 is a star that formed from gas that was substantially enriched by ejecta from a metal-poor supernova. Such a picture would indicate that metallicity in bulge stars proceeded in an inhomogeneous manner at some level.

This scenario can be tested, as ^{19}F is not the only metallicity-dependent element that has been studied in BMB78. Sodium yields from SN II are also metallicity dependent and Na has been measured in BMB78 (Table 1). Figure 3 displays results for sodium, where Na-to-O ratios are plotted versus the oxygen abundance. Field-star values of Na/O and A(O) are included as the small blue open symbols. The solid curve contains the massive-star yields from WW95 convolved with a Salpeter mass function. Sodium yields are sensitive to stellar metallicity, with the Na-to-O ratio increasing with increasing metallicity (taken here to be mapped by the oxygen abundance), and the observed field star values track this curve quite well. The bulge values of Na/O and A(O) from Cunha & Smith (2006) are shown as the large filled symbols with their associated estimated errors: note that Na abundances for BMB78 and BMB289 are presented here for the first time. Additional bulge stars from Fulbright et al. (2007) and Lecureur et al. (2007) are shown as the smaller filled symbols. The agreement in the trend of Na/O with A(O) is similar for all three bulge studies.

The sample of bulge red giants included in Figure 3 show some peculiarities compared to the field stars. First there are the two Na-rich but O-poor giants from the Fulbright et al. (2007) paper. The pattern of Na/O and A(O) found in these two stars is very similar to what is found in globular clusters and Fulbright et al. conclude that these two red giants are actually members of the bulge globular cluster NGC6522 located in Baade’s Window. All three bulge studies also contain a small number of stars that fall to the O-rich side of the distribution, with lower Na-to-O ratios. The star BMB78 is one of these examples, having a low Na abundance when compared to its large oxygen abundance. Since both F and Na have massive-star yields that increase with metallicity, whereas O does not, the low values of F/O and Na/O in this star can result from enrichment by a low-metallicity SN II. Such a picture would suggest that chemical evolution within the bulge population was not homogeneous. The small number of bulge stars that are found with lower values of Na/O may result from inhomogeneous chemical evolution.

A picture of inhomogeneous chemical evolution can be checked for consistency as illustrated in Figure 4, where the abundance ratios of F/Ti are plotted versus Na/Ti. Titanium is chosen as the fiducial element since there is evidence that oxygen yields are being altered at high metallicity by metal-rich WR winds (McWilliam et al. 2007) and Ti typifies an α -element and thus serves as a monitor of SN II enrichment. In this diagram the bulge stars fall along a sequence of increasing values of F/Ti with increasing Na/Ti; the metallicity sensitive elements F and Na increase in lockstep and, in this case, BMB78 exhibits the lowest values of F/Ti and Na/Ti, which is consistent with processed gas from a metal-poor SNII.

5. Conclusions

Fluorine abundances are measured for the first time in a sample of red-giants in the Galactic bulge. The fluorine abundances obtained generally define a steady increase in F/O versus A(O), which is reminiscent of the disk results and can be explained by production of ^{19}F in a combination of AGB and WR stars. The most oxygen-rich target in this sample has a large fluorine abundance, but no accompanying s-process enhancement, in contrast to the predictions for AGB nucleosynthesis by Goriely & Mowlavi (2000). The abundance pattern observed for this metal-rich bulge target favors ^{19}F production during the WR phase of evolution. One oxygen-rich giant in this sample, however, fails to follow the disk trend and shows a fluorine abundance, as well as sodium, that is more compatible with pollution from metal-poor SN II, where ^{19}F is synthesized by neutrino nucleosynthesis. These results may indicate that there was inhomogeneous mixing in the gas that formed the Milky Way bulge during its phase of chemical enrichment.

We thank Andy McWilliam for kindly sending us bulge s-process results prior to publication and the referee whose suggestions improved the paper. This work is supported in part by the NSF (AST06-46790) and NASA (NAG5-9213). Based on observations obtained at the Gemini Observatory, which is operated by the Assoc. of Univ. for Research in Astronomy Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the NSF (United States), the STFC (UK), the NRC (Canada), CONICYT (Chile), the ARC (Australia), CNPq (Brazil) and SECYT (Argentina). Based on observations obtained with the Phoenix spectrograph, developed and operated by NOAO.

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Table 1. Sample Stars and Derived Abundances

Star	T_{eff}	Log g	$\xi(\text{km s}^{-1})$	A(F)	A(Na)	A(O)
I-322	4250	1.5	2.0	4.50	6.13	8.60
IV-003	4500	1.3	1.8	...	4.23	8.05
IV-167	4375	2.5	2.2	<6.10:	7.30	9.10
IV-072	4400	2.4	2.2	5.60	7.35	9.20
IV-329	4275	1.3	1.8	4.30	5.30	8.35
BMB 78	3600	0.8	2.5	4.26	5.58	9.00
BMB 289	3375	0.4	3.0	4.90	6.05	8.75

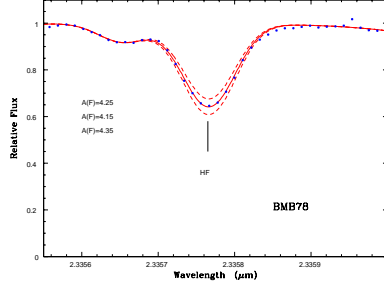


Fig. 1.— Observed (dotted line) and synthetic (solid and dashed lines) spectra of the star BMB78 in the region of the HF line. The synthetic spectra were calculated for three fluorine abundances as specified in the figure.

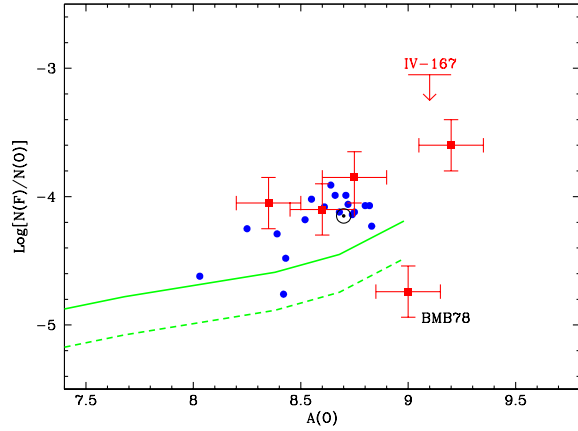


Fig. 2.— Ratios of F to O plotted versus the oxygen abundance, $A(O)$. The values of F/O in 4 of the bulge stars track the trend defined for field stars, with the O-rich star IV-072 extending the general field-star trend. The bulge star BMB78 has a low value of F/O for its O-abundance. The solid curve illustrates model values of F/O versus $A(O)$ for neutrino nucleosynthesis from Woosley & Weaver (1995), with the dashed curve representing a downward shift of the values of F/O as suggested by Heger et al. (2005).

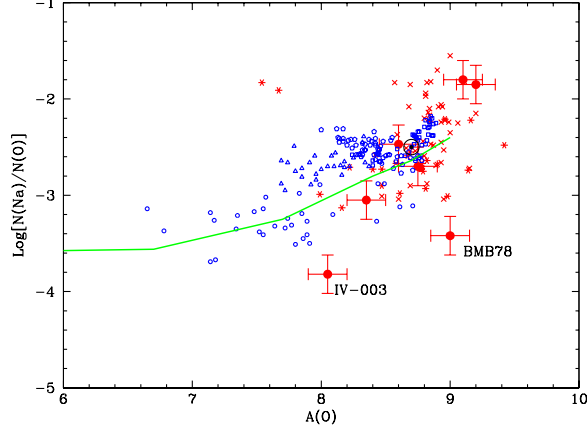


Fig. 3.— The behavior of Na/O versus O for bulge stars from this study (red circles with errorbars), Fulbright et al. (2007 - small red asteriks) and Lecureur (2007 - small red crosses). Galactic field star results are the small blue open symbols from Nissen & Schuster (1997), Fulbright (2002), Reddy et al. (2003), and Bensby et al. (2004). The solid line represents yields from Woosley & Weaver (1995) convolved with a standard IMF. Note the position of BMB78, with a low ratio of Na/O at high metallicity; this abundance pattern can result from enrichment by metal-poor SN II.

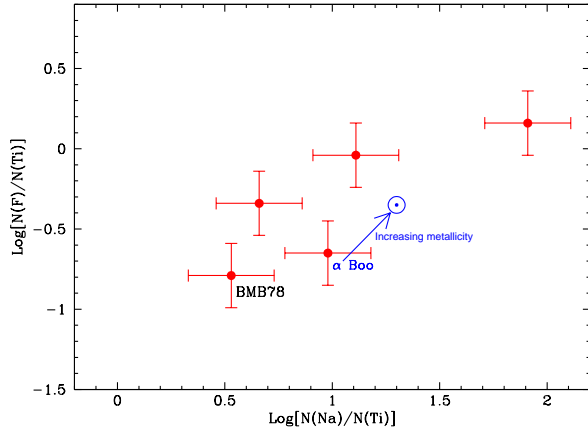


Fig. 4.— The run of fluorine over Titanium versus the abundances of sodium over titanium for the bulge targets stars and the field star α Boo (Cunha et al. 2003; Cunha & Smith 2006). The position of the sun in this diagram is also shown for comparison.